



STANFORD UNIVERSITY
DEPARTMENT OF ELECTRICAL ENGINEERING

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(1) *Title:*

**"Novel Techniques in Non-Stationary Analysis of
Rotorcraft Drivetrain Vibration Signatures"**

(2) *Type of report:*

FINAL REPORT

(3) *Principal Investigator:*

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FINAL REPORT SUMMARY

This research effort produced new methods to analyze the performance of linear predictors that track non-stationary processes. Specifically, prediction methods have been applied to the vibration pattern of rotorcraft drivetrains. This analysis is part of a larger rotorcraft Health and Usage Monitoring System (HUMS) that can diagnose immediate failures of the subsystems, as indicated by abrupt change in the vibration signature, and prognosticate future health, by examining the vibration patterns against long-term trends. This problem is described by a earlier joint paper co-authored by members of the funding agency and the recipient institutions [1] prior to this grant effort. Specific accomplishments under this grant include the following:

- (1) Definition of a framework for analysis of non-stationary time-series estimation using the coefficients of an adaptive filter.
- (2) Description of a novel method of combining short-term predictor error and long-term regression error to analyze the performance of a non-stationary predictor.
- (3) Formulation of a multi-variate probability density function that quantifies the performance of a adaptive predictor by using the short- and long-term error variables in a Gamma function distribution.
- (4) Validation of the mathematical formulations with empirical data from NASA flight tests and simulated data to illustrate the utility beyond the domain of vibrating machinery.

These three accomplishments are described briefly below.

(1) Analyzing Non-Stationary Sequences Using Coefficients of an Adaptive Filter

Although the principal use of predictors is to suggest the most likely outcome of the stochastic process at some sample point in the future, the predictor coefficients themselves can provide valuable information about the state of the process being modeled. That is, as an estimator of the process in the future, the predictor contains information about the state of the process. For processes that naturally progress from one state to another, although at an unknown rate, the current state

information can be quite valuable. The application of interest to the authors is an important example of such a process. As these systems fail, they evolve from a "healthy" state to one of several possible "failed" states. Interim states between these two end states can provide information about the likely type of failure that is causing degradation, so an important determinant of predictor performance is obviously the accuracy of the coefficients, since it is the coefficients that weight previous inputs to form a sum that represents some future value.

This framework was described in a paper by the Principal Investigator and one of the Research Associates [2].

(2) Combining Short-Term Predictor Error And Long-Term Regression Error

This framework has been extended to combine the instantaneous short-term error and the long-term regression error on the coefficients into a joint probability density that describes the performance of the predictor described above. A classical linear regression error measure is used to define confidence intervals on the coefficients. This is coupled with a short-term error measure that addresses the time-varying transitions from one state to another. Specifically, for this application, the short term error tracks coefficient accuracy as the machinery moves from "healthy" to "faulty". Confidence intervals based upon regression error are created once the process becomes temporarily stationary. A probability density function is then created over coefficient space — representing process state space — to provide a map that suggests where and how the machinery is progressing from healthy to faulty. This map will allow rotorcraft operators to make strategic decisions about flight risks related to the drivetrain.

(3) Quantifying with a Gamma Distribution

In a newer publication, we show that, when properly normalized, the short-term and regression error terms can be used as conditional variables in a Gamma distribution. In [3], it is shown that, once normalized to unit scale, these metrics are variates in a multidimensional probability density function that approaches a Gamma distribution with parameter λ determined by the degree of stationarity of the process and parameter α by the order of the filter. This method is shown to be equally valuable for

quantifying the performance of estimation filters, such as equalizers in communication channels that vary with time.

(4) Evaluating with Empirical and Simulation Data

Data from US Navy, US Army, and NASA Test Rigs, including the Ames Flying Laboratory for Integration and Test (FLITE), as documented on the NASA Ames Signal Analysis Laboratory website (<http://siglab.arc.nasa.gov>), have been used to validate the essential claims made in (1) through (3) above.

Other data sets are under construction that simulate non-stationary processes in the communications domain. Early results suggest that, in a communication domain, this technique could be used to assess the performance of equalizers (filters) for a time-varying (e.g., mobile telephony) channel: the channel capacity will slowly vary with ambient noise, signal strength, etc., but also may undergo sudden changes due to man-made and natural environmental effects, cross-signal interference, etc. In this case, similar to the drivetrain HUMS requirements, a quantifiable characterization of equalizer performance is desired to help manage overall system performance.

REFERENCES

- [1] Dzwonczyk & Huff, "Helicopter Transmission Health Monitoring Using Real- Time Neural Computing Methods," *Proceedings of the 1994 IEEE/AIAA 13th Digital Avionics Systems Conference*, pp. 359-364.
- [2] Dzwonczyk & Meng, "How Good is Your Predictor? Expanding Confidence Intervals To Define Probability Densities On Adaptive Parameters," *1999 IEEE International Conference On Acoustics, Speech, and Signal Processing (ICASSP-99)*, pp. 1233-1236.
- [3] Dzwonczyk & Meng, "Quantifying Adaptive Filter Performance by Defining Probability Densities on Weight Parameters," submitted to *2000 IEEE International Symposium on Information Theory*.